Environmental Aspects of PV Power Systems

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Executive summary

Introduction
During normal operation, photovoltaic (PV) power systems do not emit substances that may threaten human health or the environment. In fact, through the savings in conventional electricity production they can lead to significant emission reductions. There are, however, several indirect environmental impacts related to PV power systems that require further consideration. The production of present generation PV power systems is relatively energy intensive, involves the use of large quantities of bulk materials and (smaller) quantities of substances that are scarce and/or toxic. During operation, damaged modules or a fire may lead to the release of hazardous substances. Finally, at the end of their useful life time PV power systems have to be decommissioned, and resulting waste flows have to be managed.

An expert workshop was held as part of the International Energy Agency Photovoltaic Power Systems Implementing Agreement Programme, to address these environmental aspects of PV power systems. The objectives of the workshop were:
- Review/overview of issues and approaches regarding environmental aspects of PV power systems;
- Enhanced clarity and consensus regarding well-known aspects like Energy Pay-Back Time;
- Identification of issues of environmental importance regarding PV power systems (‘hot spots’);
- Identification of issues requiring further attention (‘white spots’);
- Establish a network of researchers working on PV environmental issues.

The workshop had 25 participants from Europe, the United States, Japan, and Australia, representing the researchers in the field of environmental aspects of PV systems, R&D managers, industry and utilities.

Issues and approaches
The environmental issues that are considered most relevant for PV power systems were identified in the workshop as well as the approaches that may be used to investigate them. The main environmental issues discussed at the workshop were:
- Energy use.
- Resource depletion. For example, the resource availability for indium (used in CIS-modules) and silver (used in mc-Si modules) has been indicated as potentially problematic.
- Climate change. Greenhouse gas emissions (notably CO_2) mostly originate from energy use and the potential for PV power systems to reduce these emissions is receiving increasing attention.
- Health and Safety. Continuous or accidental releases of hazardous materials can pose a risk towards workers and the public.
- Waste.
- Land use; at least in the case of ground-based arrays.

A life cycle approach is needed for the assessment of environmental aspects of PV power systems because they mostly occur at life cycle stages other than the operation of the PV power system itself (i.e. manufacturing, end-of-life waste management). This life cycle approach is incorporated in the recently developed method of environmental Life Cycle Assessment (LCA). LCA[1] involves the comprehensive assessment of all environmental impacts throughout the life cycle of a product, service, sector of the economy (like the energy sector) or the society as a whole. Due to the high degree of complexity of any comprehensive analysis framework, lack of consensus regarding the assessment of various environmental impacts, and lack of data, simplified forms of LCA have been developed and applied to the assessment of PV power systems. Energy pay back times and CO_2 mitigation potentials of PV power systems are the results of simplified forms of LCA and may be used to give a first indication of environmental aspects. Since these indicators do not express all PV specific environmental risks, Health, Safety and Environmental (HSE) assessment and control is needed as a complementary procedure.

Health, Safety and Environmental Aspects

Substances that are the subject of HSE assessment and control are (i) toxic and flammable/explosive gases like silane, phosphine, germane, and (ii) toxic metals like cadmium (in CdTe- and CIS-based technologies). The prevention of accidental releases of such hazardous substances is very important for the success of PV power systems. Current environmental control technologies seem to be sufficient to control wastes and emissions in todays production facilities. Technologies for recycling of cell materials are being developed presently. Enhanced clarity is however needed regarding costs, energy consumption and environmental aspects of these processes. Depletion of rare materials will probably not pose restrictions if further development towards thinner layers and efficient material (re)use is pursued.

The use of cadmium and other ‘black list’ metals in PV systems remains a controversial issue although the presented studies gave no indications of immediate risks. The perspective of the decision maker (risk aversion, risk comparison or risk-benefit evaluation) will determine the acceptability of new cadmium applications because this issue cannot be solved on the basis of scientific research only.

The use of hazardous compressed gases in PV manufacturing requires continuous attention. Further research and demonstration towards safer materials and safer alternatives is needed. Further progress in using less material (thinner layers) more efficiently (better deposition processes) is also needed and will lead to further reduction of energy use and emissions.

The general conclusion was drawn that the immediate risks from the production and operation of PV modules to human health or the ecosystem seem to be relatively small and well manageable.

Energy pay back times and CO_2 mitigation potential

The Energy Pay Back Time (EPBT) of a PV system is the time (in years) in which the energy

[1] Unless explicitly mentioned otherwise, LCA is used in this text as a shorthand for *environmental* Life Cycle Assessment. In a more comprehensive sense, Life Cycle Assessment also involves other (e.g. social and economic) impacts.

input during the module life cycle is compensated by the electricity generated with the PV module. The EPBT depends on several factors including cell technology, PV system application and irradiation. There still seems to be a popular belief that PV systems cannot ‘pay back’ their energy investment. The data from recent studies show however that although for present-day systems the EPBT can still be high, it is generally well below the expected life time of a PV system. For c-Si modules most energy is needed for silicon production, while for thin film (a-Si and CdTe) PV modules the encapsulation materials and the processing energy represent the largest energy requirements.
It is important to note that the potential for energy efficiency improvements is large. It seems feasible that the energy pay back time for grid-connected PV systems will decrease to two years or less in case of c-Si modules and to one year or less for thin film modules (under 1700 $kWh/m^2/yr$ irradiation, which is representative for the Mediterranean countries).
The operation of PV power plants does not involve the combustion of carbon-containing fuels and can therefore lead to a significant CO_2 mitigation potential. Indirect emissions of CO_2 occur in other stages of the life-cycle of PV power systems but these are significantly lower than the avoided CO_2 emissions. Greenhouse gas emissions other than CO_2 should also be considered. For example, fully fluorinated compounds like SF_6 and CF_4 have a very large Global Warming Potential, so their use in PV manufacturing should be avoided.

Environmental Life Cycle Assessment
The first LCA studies on PV power systems show that emissions are largely dominated by the energy use (electricity in particular) during PV production. From these results it is important to realize that the environmental performance of PV power systems heavily depends on the energy efficiency of PV system manufacturing <u>and</u> on the performance of the (national or regional) energy system itself, electricity production in particular.
The fuel mix of the electricity production system strongly determines the results of PV power system LCA’s. A careful choice of the fuel mix is therefore important. The choice of the fuel mix should be consistent with the objectives of the study and must be reported. For certain cases (like international comparisons) a ‘generic fuel mix’ could be defined.

System aspects
For grid-connected systems LCA results show that Balance-of-System (BOS) components (supporting structures, power conditioner etc.) do not seem to have a large effect on the results because most energy is required for module production. In the future this will change when module production becomes more energy-efficient. In that case BOS components become more important and grid-connected, building-integrated PV systems will then have a significant advantage over ground-mounted systems.
LCA studies are also used to compare environmental aspects of different PV system options (e.g. grid-connected versus stand-alone operation). In such analyses options for energy demand reduction must always be considered along with the assessment of PV applications.
The scope of analyses can be extended beyond the assessment of environmental impacts of the life-cycle of specific PV systems through the analysis of the (environmental, but also social and economic) impacts of PV power systems within the entire energy system or the entire society. Such analyses must consider system integration aspects like energy storage and the treatment of imports and exports.

Comparative assessments

Comparisons between PV module technologies, between Balance-of-System alternatives or between PV and non-PV power production technologies can be made on the basis of LCA results.

Such comparisons require a careful identification of the study objectives before choices are made regarding the alternatives to be compared and the environment or ‘background' where the comparison takes place (i.e. the electricity production system). In the sessions on Health, Safety and Environment, Energy Pay-Back Time, LCA and System Aspects a number of (implicit) technology comparisons were presented. Other, more general conclusions on technology comparison were not drawn during the workshop.

General conclusion

From the assessments made so far of the environmental risks of PV power systems and the possibilities regarding management of these risks, the conclusion may be drawn that, from an environmental point of view, the use of PV as a replacement for fossil fuel-based electricity generation has significant environmental benefits and there seem to be no significant bottlenecks that cannot be overcome.

Table 1 (next page) summarizes the ‘hot spots’ and ‘white spots’ identified from the workshop results.

Table 1. Summary of issues of environmental importance regarding PV power systems (‘hot spots’) and issues that require further attention (‘white spots’).

Theme:	**Hot spots**	**White spots**
Resource depletion	▸ In/Ga/Te/Ag supply ▸ Efficient resource use	▸ physical and economic constraints for In/Ga/Te/Ag supply ▸ prospects for thinner cell layers ▸ prospects for more efficient material utilization ▸ module recycling technology and its efficiency ▸ design of recyclable systems
Energy use	▸ reducing energy use for silicon production ▸ energy use for module frames and BOS	▸ energy consumption of solar grade Si processes ▸ energy consumption of recycling processes ▸ energy-efficient frame and BOS designs
Climate Change	▸ CO_2 mitigation potential of PV technology ▸ release of Fully Fluorinated Compounds (FFC’s) from plasma processing ▸ energy-efficient demand side options ▸ sensitivity of results for fuel mix of conventional electricity supply	▸ CO_2 mitigation potential of autonomous PV systems ▸ alternatives for use of FFC’s in PV production ▸ role and impact of dynamic assessment methods
Health & Safety	▸ management of compressed dangerous gases ▸ use of ‘black list’ materials (e.g. Cd)	▸ safer materials and safer alternatives ▸ prospects for thinner cell layers ▸ prospects for more efficient material utilization ▸ long term risks from (low-level) releases of black list materials
Waste	▸ concentration/leaching of heavy metals from modules ▸ module waste management options (incl. recycling)	▸ environmental aspects of relevant waste management methods

List of abbreviations

a-Si	amorphous Silicon
BIPV	Building Integrated PV
BOS	Balance Of System
CdTe	Cadmium Telluride
CIS	Copper Indium Selenide
c-Si	crystalline Silicon
ECU	European Currency Unit
EPBT	Energy Pay-Back Time
ERF	Energy Return Factor
EU	European Union
ExternE	Externalities of Energy
FFC	Fully Fluorinated Compounds
GWP	Global Warming Potential
GHG	GreenHouse Gas(ses)
HSE	Health, Safety and Environment
IEA	International Energy Agency
LCA	Life Cycle Assessment
LT	Life Time
mc-Si	multicrystalline Silicon
Novem	Netherlands Organisation for Energy and the Environment
OECD	Organisation for Economic Co-operation and Development
PV	photovoltaic
PVPS	Photovoltaic Power Systems

Workshop objectives

- Review/overview of issues and approaches regarding environmental aspects of PV power systems;
- Enhanced clarity and consensus regarding well-known aspects like Energy Pay-Back Times;
- Identification of issues of environmental importance regarding PV power systems (‘hot spots’);
- Identification of issues requiring further attention (‘white spots’);
- Establish a network of researchers working on PV environmental issues.

Workshop background

The IEA PVPS programme
The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD) which carries out a comprehensive programme of energy co-operation among its 23 member countries. The European Commission also participates in the work of the Agency. The IEA Photovoltaic Power systems Programme (PVPS) is one of the collaborative R&D agreements established within the IEA, and, since 1993 its Participants have been conducting a variety of joint projects in the applications of photovoltaic conversion of solar energy into electricity. The overall programme is headed by an Executive Committee composed of one representative from each participating country, while the management of individual research projects (Tasks) is the responsibility of Operating Agents. Currently seven Tasks have been established. The twenty two members are: Australia, Austria, Canada, Denmark, European Commission, Finland, France, Germany, Israel, Italy, Japan, Korea, Mexico, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, The United Kingdom, and The United States of America. The objective of Task 1 is to promote and facilitate the exchange and dissemination of information on the technical, economic and environmental aspects of photovoltaic power systems for utility applications and other users in participating countries.

The workshop
The workshop entitled “Environmental Aspects of Photovoltaic Power Systems” has been organized as part of the IEA PVPS programme. It is Task 1 (exchange and dissemination of information on PVPS) of this programme under whose auspices the workshop was held. The organizing committee of the workshop consisted of representatives from the following countries participating in Task 1: Japan, Switzerland, Denmark, Sweden and The Netherlands. The Netherlands was the coordinating country through the Netherlands Organization for Energy and the Environment (Novem). Novem has commissioned Evert Nieuwlaar and Erik Alsema (Utrecht University, Department of Science, Technology and Society) for the preparation, the execution and the reporting of the workshop.
In the preparation of the workshop the Task 1 members identified the experts who are in their country working on environmental aspects of PV power systems. A screening of the experts identified and the work done so far by these experts resulted in an inventory of experts along with a list of topics that were to be addressed by the workshop. Approved by the organizing committee, the workshop objectives were formulated and a workshop program worked out with the topics to be addressed.

Participants
The workshop had 25 participants from Europe, the United States, Japan and Australia. The participants represented the researchers in the field of environmental aspects of PV systems, R&D managers, industry, utilities and IEA PVPS Task 1 itself. The list of participants is included in appendix A-2. The fifteen papers that were presented at the workshop can be found in appendix B of this report. A selection from these papers will be published the Journal ‘ Progress in Photovoltaics’ along with an article summarizing the main results of the

workshop.

Workshop program

The following sessions were held (the full workshop program can be found in appendix A-3):
Session 1 - Starting Session: Perspectives, Issues and Approaches
Session 2 - Health, Safety and Environmental (HSE) aspects of cell technologies
Session 3 - Energy Pay-Back Times (EPBT) and CO_2 mitigation potential
Session 4 - Environmental Life Cycle Assessment
Session 5 - System Aspects
Session 6 - Comparative Assessment
Session 7 - Concluding Session

Session 1: Starting session: perspectives, issues and approaches

In the starting session the subject of the workshop was addressed from various perspectives and an overview of issues and approaches was presented and discussed.

Regarding the perspectives from the various stakeholders, presentations were given on the IEA/governments/R&D perspective (Erik Lysen, Jacques Kimman), the utilities' perspective (Ola Gröndalen (appendix B-1), Daniel Dijk) and a PV manufacturer's perspective (Mike Patterson). Highlights from these presentations are:

- From the IEA PVPS Task 1 perspective clarity about environmental aspects towards decision makers is important. Misconceptions regarding long energy payback times have to be taken away. A consensus is needed regarding methods used and order of magnitude of the results.
- From the R&D perspective it is never too early to start looking at environmental aspects of new technologies. Even when real implementations of the technology are not available yet, as with organic solar cells, clarity regarding environmental aspects is needed to help decision makers in making priorities.
- For the electricity supply industry it is important to recognize that electricity plays a key role in the transition to a sustainable energy supply. Despite its large potential, significant efficiency improvements and cost reductions, substantial effort is still required to bring PV into the market at a substantial scale. If and when any serious environmental concerns would come up, they are expected to be solved.
  In order to facilitate the comparison of energy supply options, a wish for manageable overviews of avoided versus emitted substances per technology pair (e.g. coal vs. PV) was expressed by the electricity industry.
  Furthermore, an issue which must not be overlooked with respect to large-scale implementation of PV technology is the effects of electricity storage systems. Such storage systems will be required for remote power applications (e.g. batteries) and also for grid-connected PV when high penetration levels are reached (e.g. pumped hydro, hydrogen).
- From the manufacturing industry perspective the concern is that their products must be environmentally friendly throughout all stages of their life cycle (manufacturing, during the lifetime, end of life).

An overview of issues and approaches was given by Nieuwlaar (appendix B-2). The environmental issues involved in PV power systems are related to (i) the use of energy, (ii) the use of relatively large quantities of bulk materials, and (iii) the use of exotic materials that are scarce and/or toxic. The environmental themes that are considered to be relevant for PV power systems include:

1. Energy use. Energy performance indicators like Energy Pay-Back Time (EPBT) have a function, although limited, in quantifying environmental stress.
2. Resource depletion. Some studies have identified indium used in CIS-modules and silver used in mc-Si modules as potentially problematic.
3. Climate change. Emissions of greenhouse gases (notably CO_2) are mostly caused by the direct and indirect use of fossil energy carriers in the production stage of PV power

systems. At some places also process emissions of CO_2 and other greenhouse gases take place.

4. Health and Safety. Continuous or accidental releases of hazardous materials can pose a risk towards workers and the public.
5. Waste. Waste management during manufacturing and end-of-life requires particular attention.

One supplementary theme which was brought forward during the discussion was:

6. Land use. The use of land area may also be viewed as an environmental impact of PV systems, at least in the case of ground-based arrays.

Life-cycle approaches are needed to address the environmental impacts of PV power systems because these impacts originate mostly from manufacturing and end-of-life management. Environmental Life Cycle Assessment (LCA[2]) is the appropriate tool at least for making inventories and the assessment of energy related emissions. The calculation of energy payback times and CO_2 mitigation potentials can be seen as special forms of performing life-cycle assessments. Health, Safety and Environmental (HSE) assessments complement the LCA approach by addressing the issues that cannot be generically addressed by LCA.

[2] Unless explicitly mentioned otherwise, LCA is used in this text as a shorthand for *environmental* Life Cycle Assessment. In a more comprehensive sense, Life Cycle Assessment also involves other (e.g. social and economic) impacts

Session 2 - Health, Safety and Environmental (HSE) aspects of cell technologies

General

HSE assessment and control address the health, safety and environmental risks associated with processes and plants. Although it looks at specific places or stages in the life cycle, the identification, analysis and control of such risks throughout the life cycle is pursued. The following life-cycle stages are the subject of HSE assessment for PV power systems:

- PV manufacturing (accidental or continuous releases of hazardous materials, waste management at production facilities)
- PV operation (risks caused by damaged modules, fire hazards)
- End-of-life waste management of PV power systems (recycling, (controlled) landfill)

Substances that require attention in the light of HSE control are (i) toxic and flammable/explosive gases like silane, phosphine, germane, and (ii) toxic metals like cadmium (in CdTe- and CIS-based technologies) and lead (in Si-based technologies).

Since the PV manufacturing industry shares a number of processes with the semiconductor industry, it can benefit from sharing experiences with respect to environmental impacts and HSE management.

Status - material resources

Some module types require materials which are limited in supply, either because the resource is scarce or because it occurs in such low concentrations in ores that it can only be mined economically as a by-product of another material. For these reasons supply limitations require attention for materials like indium, gallium and tellurium.

However, if further development towards thinner layers and efficient material (re)use is pursued depletion of rare materials will probably not pose restrictions (see Zweibel's discussion of this subject in Appendix B-11).

Status - manufacturing

A large number of options exist for the prevention and control of accidental releases of hazardous materials in PV facilities (Fthenakis, appendix B-3). A number of protection layers can be identified for prevention and mitigation of accidental releases:

- safer technologies, processes, and materials;
- safer use of materials,
- prevention of accident-initiating events,
- safety systems,
- capturing accidental releases and options to prevent human exposure and their consequences.

Significant advances have been made to reduce the risk of handling hazardous gases in semiconductor and photovoltaic facilities. In his paper presented to the workshop Fthenakis states, however, that the materials have for the most part remained the same. He points out that safer forms of toxic doping materials have been introduced but further research will be needed on safer materials (e.g. disilane as a replacement for silane) and on higher material utilization at the process level.

The use of safer materials is also stressed in the contribution by Zweibel on environment, safety and health impacts from thin film PV (appendix B-11). In his paper he invites potential manufacturers of thin films to consider an aggressive approach to environment, safety and health impacts. Since most HSE issues are directly proportional to the use of certain materials and material costs are a key driver for manufacturing, using less material also means cheaper PV for the manufacturer. Thinner layers and more efficient use of materials must therefore be pursued. From Zweibel's paper: an order-of-magnitude reduction in layer thickness in comparison to today's normal thicknesses is considered practical and thicknesses of 0.2-0.5 micron should be assumed for any calculations and projections about the future, highly evolved thin-film PV technologies (e.g. post-2020).

The management of wastes associated with thin film PV manufacturing was studied as part of a EU-sponsored project on upscaling of thin film PV manufacturing. The paper presented by Patterson (appendix B-4) reported the results of this project. For CdTe, CIS and amorphous Si-based technologies the nature and quantities of wastes have been identified and the status of waste management techniques described. For CdTe and a-Si based technologies present waste treatment techniques are considered suitable to enable satisfactory management of these wastes. For CdTe and CIS based technologies further work is needed to improve deposition techniques in terms of material efficiency.
With respect to a-Si technology the possible emission of SF_6 is a point of attention. This gas which is used for plasma reactor cleaning, should be avoided because it is a very strong greenhouse gas (cf. discussion on CO_2 emissions in Session 3).

Status - system operation
During normal operation of a PV system, a release of critical elements into the environment and, finally, to humans can only occur as a consequence of accidents (broken modules, fire). Scenarios in which toxic elements are released from CdTe or CIS modules due to such accidents were investigated by Steinberger (appendix B-5). Based on data from leaching experiments the concentrations of heavy metals in water and soil as a result of module breakage were estimated and compared with regulatory limit values. These investigations gave no indications of acute danger for human beings or the environment from the operation of CdTe and CIS modules in rooftop installations. (Note, however, that long-term risks for human health or the environment are not expressly ruled out by these results).

Status - end of life waste management
Although no presentations were given on this subject, the workshop identified the need for enhanced clarity regarding end-of-life management of module waste and regarding module recycling options. Under existing environmental regulations in some countries or states CdTe, CIS or c-Si modules[3] may be classified as hazardous waste, needing a special disposal procedure. Although CdTe and CIS modules will be accepted by non-ferro smelters as a fluxing agent, thus allowing recycling of the modules, this method does not seem a viable solution for large scale recycling of these modules. In the USA efforts are therefore underway to develop dedicated recycling methods for CdTe and CIS modules but at this moment there is

[3] For c-Si due to the lead in soldered connections.

little information on costs, energy consumption and environmental aspects of these processes. In Europe no activities in this field are known[4].
Our conclusion is that the whole issue of the recycling of PV modules and other system components, including module design options, waste collection schemes, processing methods and environmental and cost impacts are still very much a 'white spot'.

Risks from cadmium and other 'black-list' metals
The use of cadmium and other 'black-list' metals in PV modules remains a controversial issue. Although the presented studies gave no indications of immediate risks due to the cadmium content of CdTe modules, the question whether cadmium-based PV modules are environmentally acceptable remains one to which no single yes or no answer can be given.
As with all new technologies the acceptability will depend on the perspective of the decision maker. In a no-risk approach all new applications of black-list substances are ruled out. Other approaches may be to compare risks of different technology options (e.g. coal vs. PV), to compare the risks with those of other accepted activities in society or to assess risks versus benefits of the new technology. Elements for such approaches have been discussed elsewhere by Steinberger [Steinberger, 1996] and Alsema [Alsema, 1996; Alsema et al., 1997].
In view of this dependency on the evaluation perspective we think that further scientific research can contribute only to a limited extent towards solving the controversy on the cadmium-based PV modules. In other words this issue is more a 'political white-spot' than a 'scientific white spot'.

Nonetheless some areas can be identified where further scientific work may be helpful, namely:
1) investigation of waste management and module recycling options;
2) estimation of the expected rate of 'leakage' of cadmium and other heavy metals from the module life cycle into the environment, for the different waste management options;
3) long-term risks from these emissions to human health and the ecosystem, especially in the case of large-scale implementation of PV systems.

Conclusion
A general conclusion to be drawn from this session is that the *immediate* risks from the production and operation of PV modules to human health or the ecosystem seem to be relatively small and well-manageable. Remaining white spots of a scientific nature mainly concern the options for and (long-term) effects of module waste management and recycling.

Recommendations
- The use of hazardous compressed gases in PV manufacturing requires continuous attention. Further research and demonstration towards safer materials and safer alternatives is needed. In addition, risk awareness and training of personnel are extremely important.
- Further progress in efficient material utilization is needed and will significantly lead to further reduction of energy use, emissions and accidental risk.

[4] After the workshop, the Swedish research and development organization Elforsk commissioned Sydkraft Konsult AB to work on "environmental aspects of solar cells concerning disposal, recycling and reuse of photovoltaic modules...". The work is planned to start in 1998.

- For the same reasons further progress towards thinner films is needed
- Enhanced clarity regarding end-of-life management of module waste and regarding module recycling options is needed.

Session 3 - Energy Pay-Back Time (EPBT) and CO_2 mitigation potential

General

Although PV power systems do not require finite energy sources (as it is the case for fossil and nuclear systems) during their operation, a considerable amount of energy is needed at present for their production. The environmental issues associated with this energy use for PV manufacturing will also affect the environmental profile of PV Power systems. The environmental themes that are strongly related to the energy system are: exhaustion of finite energy carriers, climate change and acidification. For climate change and acidification this relation is strong since the largest part of greenhouse gas and acidifying emissions originate from energy conversion systems. One may consider using energy performance (e.g. Energy Pay Back Time) as an indicator for the environmental stress caused by PV power systems. Such indicators are strong regarding the exhaustion of finite energy sources, reasonably strong regarding climate change and acidification and weak or failing regarding themes like toxicity. In cases, like Switzerland, where the electricity mix for PV manufacturing is heavily based on hydro and nuclear power this observation does not hold however.

Unfortunately, it seems to be a popular belief that PV systems cannot ‘pay back’ their energy investment. Therefore, it is important to investigate this issue on the basis of solid data.

Energy Pay Back Time

The Energy Pay Back Time is defined by EPBT = E_{input}/E_{saved}, where E_{input} is the energy input during the module life cycle (which includes the energy requirement for manufacturing, installation, energy use during operation, and energy needed for decommissioning) and E_{saved} the annual energy savings due to electricity generated by the PV module. For PV power systems the EPBT depends on a number of factors: cell technology, type of encapsulation, frame and array support, module size & efficiency, PV system application type (autonomous or grid-connected) and, finally, PV system performance as determined by irradiation and the performance ratio. EPBT is also affected by factors that do not directly relate to the characteristics of the PV power system itself: conversion efficiency of the electricity supply system and energy requirements of materials like glass, aluminum etc.

In his review of energy analysis studies on thin-film (a-Si and CdTe) PV modules presented at the workshop, Alsema (appendix B-6) showed that

- the EPBT of frameless thin film modules is below 2 years for present-day technology (at 1700 kWh/m^2/yr irradiation, which is representative for Mediterranean countries)
- encapsulation materials and direct processing energy form the major part of the energy use
- a frame may add up to 0.6 years to the EPBT
- in the future EPBT of less than 1 year is feasible for frameless thin film modules

Kato (appendix B-8) presented an overview of the work done in Japan on c-Si, mc-Si and a-Si based rooftop systems. The analysis included the Balance of System (supporting structure & power conditioner). The results for (current state-of-the-art) monocrystalline-Si based systems depend on the choice made regarding allocation of energy to off-grade silicon from the semiconductor industry. If off-grade silicon is treated in the same way as silicon used in the semiconductor industry and if part of the energy consumption is allocated to the SiH_4

byproduct, the EPBT of the rooftop system would be 9 years. If no energy use is allocated to off-grade silicon, the EPBT would be 3.3 years. (For a system under 1430 kWh/m²/yr irradiation, Performance Ratio of 0.81).
Kato also considered near-future module production technology based on a dedicated solar-grade silicon process in combination with electromagnetic casting of mc-Si ingots. For this type of production technology the EPBT of the rooftop system was estimated at about 2 years. For systems based on a-Si modules too, an EPBT of about 2 years was found.

Crystalline silicon modules
The analyses by Kato show that the EPBT of present-day crystalline silicon modules is affected very strongly by its dependency on silicon feedstock which was originally prepared for the electronics industry. Because the (energy) costs of silicon are probably very small in the electronics industry's products, this situation will improve only when the Si demand from the PV industry is large enough to sustain dedicated production processes for Si feedstock ('solar-grade Si'). On the other hand, if one considers a substantial role of PV in future energy supply one may assume that solar-grade Si feedstock will have replaced the energy-intensive electronic-grade Si for PV manufacturing.

Furthermore one should note that in other presentations at the workshop (e.g. Baumann, appendix B-10; Frankl et al., appendix B-15) as well as in another recent publication [Nijs et al., 1997] lower values for the energy requirement of present-day monocrystalline silicon modules were presented, leading to system EPBT values ranging from 5 to 10 years (under the same conditions as Kato's systems). The reasons for these different results have been clarified to some extent during the workshop, but nonetheless we have to conclude that a clear understanding of the energy requirements of present-day crystalline silicon modules is still lacking. In itself this would not be such a problem, if it did not hinder a good insight into the future energy balance of c-Si modules. Therefore our opinion is that the issue of the energy requirements of *present-day and future* crystalline silicon modules, should still be regarded as a 'white spot'. In this context a further clarification of the impact from different process routes for Si feedstock production is also needed.

System aspects
System aspects like Balance-of-System components, autonomous or grid-connected systems, building integration, and energy demand management options strongly influence the results of EPBT evaluations. These aspects were discussed in the session on system aspects (session 5). It has to be remarked, however, that the energy payback times of autonomous PV systems have not been addressed specifically during this workshop. So all remarks and conclusions concerning EPBT given here relate only to grid-connected PV systems. However, indications were given during the meeting that batteries would significantly increase the EPBT.

Indicators
The energy payback time as an indicator of energy performance has an appeal because of its similarity with economic payback times. A drawback of EPBT is that it does not account for the energy gain during the rest of the economic lifetime. The workshop expressed a desire for an indicator that combines EPBT with economic lifetime. An indicator that fulfills this

requirement is the *energy return factor* (ERF) which expresses the total amount of energy saved per unit invested energy. The formula resembles the one for energy payback time: ERF $= (E_{saved} * LT) / E_{input}$, where LT represents the economic lifetime. Obviously, modules with longer lifetimes will perform better using the ERF-indicator. A disadvantage of the ERF indicator is that it is not additive, i.e. ERF values of different system components cannot be added to obtain the ERF of the total system.

Greenhouse gas emissions
The potential for reduction of greenhouse gas emissions is an important issue for PV power systems. Greenhouse gases comprise not only CO_2 but also a number of other gases. The greenhouse effect from a specific gas is usually indicated as its Global Warming Potential (GWP) relative to CO_2, so that the total Greenhouse Warming Equivalent of the greenhouse gas emissions can be expressed as a CO_2-equivalent amount.
Now an approach similar to EPBT can be used to determine CO_2 pay-back times (or rather: CO_2-equivalent pay-back time) as a measure for the climate change mitigation potential associated with PV power systems. Alternatively, cumulative CO_2-equivalent emissions can be recorded per kWh in order to compare them with CO_2-equivalent emissions from alternative power production technologies.
For a large part the CO_2 emissions originate from the direct and indirect use of fossil energy carriers in the life cycle of the PV power systems. In addition to these energy-related emissions, however, other CO_2 emissions occur. Examples are the CO_2 emissions caused by the silica reduction process and the CO_2 emissions from the consumption of carbon electrodes in aluminum production. Currently, these latter emissions are estimated to be substantially smaller than the emissions associated with the energy use.
Greenhouse gas emissions other than CO_2 should receive adequate attention since some of them have a large Global Warming Potential, so that relatively small emissions of those gases can have a significant contribution to the total Global Warming Equivalent. Examples of such substances are SF_6 or CF_4, gases which may be used in plasma etching processes or in the cleaning of reactor chambers. Release to the atmosphere of 1 kg of these gases will cause a greenhouse effect equivalent to 24,000 respectively 6,500 kg of CO_2 [IPCC, 1996][5]. Thus, an SF_6 emission of 0.5 g/Wp, which was reported for one specific a-Si module production plant [Alsema et al., 1997], could result in an increase of the CO_2 pay-back time of the module with no less than 17 years[6] !
So the use and certainly the emissions of Fully Fluorinated Compounds must be avoided. Alternative cleaning methods and other techniques under development within the semiconductor industry will help to achieve this.

The results presented by Kato (appendix B-8) showed that CO_2 emissions for silicon-based

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5 These global warming potentials are given here for a 100 years time horizon. For 20 years they are (for SF_6 and CF_4 respectively) 16300 and 4400. For 500 years the global warming potentials are 34900 and 10000.

6 An emission of 0.5 g SF_6 per WP is equivalent to 0.5 g x 24,000 = 12 kg CO_2 per WP, while the avoided CO_2 emission can be calculated as 1.4 kWh/WP/yr x 0.5 kg CO_2 /kWh = 0.7 kg CO_2 /yr. Note, however, that there are no indications that the reported SF_6 emission is exemplary for the a-Si industry as a whole.

rooftop PV power systems in Japan are less than 25 g-C/kWh, except for c-Si when CO_2 emissions from Si material production are fully included[7]. Compared with an average of 126 g-C/kWh for the average electrical output of the Japanese utilities, a significant potential for CO_2 emission reduction exists.
The study presented by Inaba (appendix B-7; Komiyama *et al.,* 1996; Tahara *et al.,* 1997) showed that the choice of system boundaries is of large significance especially when the manufacturing and the installation of modules are performed in different countries, due to difference in the electricity supply mix.

Guidelines for analysts
We have seen that comparison of energy/CO_2 analysis studies is often unnecessarily difficult because of differences and lack of clarity in the methodological approach and the reporting format (also see paper B-6, section 2 and paper B-7).
Therefore we recommend to:

- aim for more clarity on:
  * system boundaries (including the way in which end-of-life disposal is treated);
  * module encapsulation and framing;
  * the evaluation of indirect processing energy;
  * Gross Energy Requirements of input materials;
  * allocation schemes used in the calculations

- Express energy requirements
  * on the basis of module area;
  * separately for thermal energy, electrical energy (specifying the supply mix) and "feedstock energy",

  or:
  * as equivalent primary energy units;

Conclusion
A final conclusion from this session is that PV technology definitively offers a significant potential for energy savings and CO_2 mitigation. Although the energy payback time and the CO_2 payback time for present-day systems is still relatively high, especially for crystalline silicon modules, it is generally lower than their expected life time.
Most important, however, is that it seems feasible to achieve a future decrease of the energy/CO_2 payback time for *grid-connected* PV systems to two years or less in case of c-Si modules and to one year or less for thin film modules(under 1700 kWh/m²/yr irradiation).

Recommendations
- enhance the energy efficiency in PV manufacturing, especially in Si feedstock production;
- avoid the use of fully fluorinated compounds such as SF_6 and CF_4 in PV module production.

[7] Note that 1 kg C is equivalent to 44/12=3.67 kg CO_2.

Session 4 - Environmental Life Cycle Assessment[8]

General
The determination of cumulative energy requirements and CO_2 emissions caused by PV power systems are specific forms of the more comprehensive activity called (environmental) Life Cycle Assessment (LCA). In principle, LCA addresses all environmental aspects throughout the complete life cycle of products and services. The comprehensiveness and complexity of processes, emissions and the determination of impacts have led to simplified procedures like EPBT and the determination of Global Warming Equivalents (i.e. equivalent CO_2 emissions). As a complement to the physical description of emissions and impacts of PV power systems, attempts have also been made to determine the external costs by monetarizing the environmental impacts as part of the EU Externalities of Energy (ExternE) project (Baumann, appendix B-10; Sørensen appendix B-14).

LCA results
The results presented by Dones (appendix B-9) on slanted roof systems and large PV power plants in Switzerland show that most of the emissions originate from the energy requirements, in particular electricity. The rest is from production of input materials and, to a minor extent, directly from specific processes of the PV chain. From this result it is important to realize that the environmental performance of PV power systems heavily depends on the energy efficiency of PV system manufacturing and on the performance of the (national or regional) energy system itself, electricity production in particular. Accounting for future developments in the energy sector as well as in PV systems, Dones shows that, for example, greenhouse gas emissions caused by PV power systems can significantly decrease in the future. Also, the emissions associated with the material production will have a higher relative importance in future systems as compared to current systems.

In her presentation on the LCA of a ground-mounted and a building-integrated PV system, Baumann presented CO_2, SO_2 and NOx emissions for the Toledo (Spain) power plant and the Newcastle BIPV facade system (appendix B-10). Comparing the emissions of the facade system (130 g-CO_2/kWh, 0.2 g-SO_2/kWh, 0.3 g-NOx/kWh) with average 1995 UK electricity generation mix (519 g-CO_2/kWh, 0.62 g-SO_2/kWh, 1.22 g-NOx/kWh) it can be noted that this PV system leads to 66-75% emission reduction. These numbers will be significantly improved in the future when further developments lead to considerable reductions in material and energy requirements. Baumann also tried to express the results in terms of external cost using results from the EU ExternE project. For the acidifying emissions an estimate of 2 and 3 mECU/kWh was found for the Toledo and the Newcastle system respectively, while a range of 1-500 mECU/kWh was estimated for the environmental costs of fossil fuel inputs into PV manufacture. The comments made by Baumann while presenting these results in her paper must be underlined here: “The uncertainties in both the climate system and the various impact pathways make accurate damage assessment very problematic”.
The opinion of the workshop participants is that results from an LCA study should always be

[8] Note that Zweibel’s paper (appendix B-11) is discussed in the section on HSE aspects (session 2)

quoted in physical terms first, before they are monetized or otherwise cumulated in an impact assessment procedure.

Fuel mix

A methodological issue which came forward during this session is that the LCA results are determined very strongly by the choice of the ‘fuel mix’ for the electricity production system. When a different choice of a country or view year can result in a drastically changed outcome, the question arises how to cope with this sensitivity and the resulting ambiguity.
Although no general recipe is available, a few guidelines can be given:

1) the choice of fuel mix should be made in accordance with the objectives of the LCA study
2) the fuel mix itself and the sensitivity of results on the fuel mix choice should be reported clearly along with the results;
3) in some cases it may be useful to use a ‘generic fuel mix’ which is obtained for example by averaging over a number of countries and/or a number of years.

Dynamic LCA

A somewhat related issue was addressed by Real in his presentation “Metabolism of sustainable Electricity Supply, exemplified with PV” (no paper available). Real aims to analyse the possibilities of the PV solar breeder concept and the effects of committing fossil fuels for production of PV systems. For this purpose he uses a simulation tool which was developed for dynamic system analysis.
His presentation and other remarks made during the workshop made it clear that there is a need for dynamic forms of life cycle assessment. Such analyses can help to assess the requirements on material and energy flows in society when substantial amounts of PV systems are introduced.

Consideration of the presented LCA studies showed that results are generally consistent: where there are differences, we understand why (e.g. counting of impacts from feedstocks or from frame and support). Also it was concluded that there are still data gaps especially regarding recycling of modules but also for other components of the PV power systems (e.g. copper in wiring, inverters). However, the data gaps are not expected to dramatically influence the main conclusions from the LCA studies.

Conclusion

A final conclusion from this session may be that the first LCA studies on PV show a dominant effect from the energy consumption during PV production. This leads to the situation that the assumed performance of the surrounding energy supply system (e.g. electricity production system) strongly affects the environmental profile of PV systems, making interpretation of results more difficult.
For future PV systems a relatively larger influence from materials production and reduced effect from energy consumption are expected.

Recommendations

- Regarding reporting LCA results:

- Clearly define target group of your LCA
- Clearly quote all assumptions: what is included, omitted
- Electricity and heat inputs should be quoted separately
- The choice of the fuel mix in electricity production should be consistent with the goal of the study.
- quote results in physical terms, even if they are monetized

- Recycling is very important for keeping LCA impacts low. Recycling is a must for PV.

Session 5 - System Aspects

The environmental aspects of PV power systems cannot be assessed without considering system aspects. Examples of such aspects are:
- Balance-of-System (BOS) components like support structures, batteries and inverters;
- Grid-connected or autonomous (i.e. stand-alone) system operation;
- Installation type: large ground-based PV arrays or decentralized building-integrated systems;
- Effects from energy demand management options;
- Effects of (large scale) integration of PV power systems into the national energy system.

For present-day PV power plants and building-integrated PV systems, the Balance of System components do not seem to have a very large effect on the EPBT. Baumann (appendix B-10) reports that the BOS-components contribute only 14.6% to the total energy requirement of the Toledo power plant in Spain. For the Newcastle BIPV facade this is 11%.
A similar conclusion can be drawn from the results presented by Frankl (appendix B-15), who analysed several existing building-integrated PV systems along with the 3,3 MWp ground-based plant at Serre. In present-day systems most energy is needed for production of the crystalline silicon modules. However, Frankl’s analysis also shows that in the future the role of BOS components will become more important and that building-integrated systems will then have a significant advantage over large PV power plants in terms of energy payback time and avoided CO_2 emissions.

The importance of energy demand management and the choice between grid-connected and standalone systems is shown in the presentation of Watt and coworkers (appendix B-12) on the LCA of PV power systems for Australian household energy supply. Their case-study shows that, in this particular case, a grid connected PV system used to supply an energy efficient rural household (originally 2 km from nearest grid) is the best option in terms of life-cycle air emissions (of CO_2, SO_2 and NOx). Decision making between the various options regarding demand management and grid-connected vs. stand-alone will be a site-specific issue and dependent on the impacts that are considered important. As part of this research Johnson also presented the results of an energy analysis of inverters for grid-connected PV systems (appendix B-13). It is shown that the energy requirements for the production of the inverter are minimal compared to those of a comparably sized PV array.

Regarding batteries, Gröndalen (appendix B-1), gave an English summary of a Swedish LCA study by Setterwall on a PV System used for electrifying a summer house at a latitude of 60^o north in Sweden. The (lead acid) batteries account for the major part of the energy requirements during manufacturing and operation. A life cycle analysis of batteries for stand alone PV systems performed in the Netherlands by IVAM (Brouwer and Lindeijer, 1993). The analysis indicated that batteries are responsible for most of the environmental impacts due to the relatively short life span and its heavy metal content. Although a large part of the batteries is recycled, a relatively large part of total energy and raw material consumption of the system is applied for the production and assembly of batteries together with a large part of the emissions and waste which are generated. Technical improvement of the batteries is needed to improve the total environmental performance of stand alone PV systems

The analyses discussed so far were focussed on specific PV power systems. Sørensen (appendix B-14) discussed issues that require attention when LCA is extended to a higher level, for example when the integration of PV power systems into a nation's energy supply system or society as a whole is analysed. Cumulative impacts are then determined by summing up the impacts from each device in the energy system. However, in such 'system level' analyses one must be aware of the possibility of double counting: part of the electricity generated is used indirectly by the energy system by manufacturers not explicitly modelled. The impacts of this electricity use should not be included for the second time in the analysis. Sørensen pointed out that such double counting can be avoided by simply omitting energy-related impacts from the indirect side-chains. Further extension of the LCA framework also involves the assessment other than environmental impacts, including social and economic impacts (see Kuemmel, Krüger and Sørensen, 1997).

Conclusion

For present day grid-connected PV power systems, the Balance-of-System represents a small part of the total energy requirement. This part will become more important when the energy efficiency of cell and module production increases, leading to significant benefits for, e.g. building integrated PV systems.

Often a wide range of BOS choices exists and decision making between the various options will be a site specific issue and dependant on the relative importance of different issues. LCA can provide a useful comparison tool for the decision making process. For this purpose the incorporation of other environmental themes besides energy in LCA studies on PV Balance-of-System choices will need more attention.

Recommendations

- Efficiency measures at the demand side can outweigh supply options and should always be considered for PV systems.
- Recycling data needed, particularly for BOS components.
- Manufacturers should prepare PV power systems for easy recyclability by adopting proper component designs and by marking the different materials used.

Session 6 - Comparative Assessment

Almost any assessment of environmental aspects of PV power systems involves an element of comparison. Such comparisons are made to assist in interpretation of the results obtained and to provide essential information to decision making. The following types of comparison can be identified in the case of PV power systems:

- comparison between PV cell types (e.g. crystalline and thin film technologies)
- comparison between Balance-of-System alternatives (e.g. stand-alone vs grid-connected, ground-mounted vs building integrated)
- comparison between PV power systems and competing non-PV power systems (e.g. PV vs coal fired power plant)

Since continuous developments are taking place, historic and projecting comparisons are also made where the current state of the art is compared with earlier results (historic) or with future expected performance (projective). As an example: energy payback times calculated today show that the invested energy in PV systems can be recovered well within the lifetime of the PV system, whereas similar calculations made in the seventies made PV a controversial technology.

Comparisons between PV cell technologies have implicitly taken place in session 3 on Energy Pay Back Times and CO_2 mitigation potentials.

Regarding Balance of System alternatives, it was already shown that building integrated PV concepts are likely to have comparative environmental benefits relative to ground mounted systems. More generic conclusions regarding BOS-impacts per application type can hardly be given because of the large variations in design alternatives and site specific aspects. This can be identified as a ‘white spot’.

The comparison of PV power systems with competing non-PV power production systems makes it possible to quantify the environmental merits of PV power systems. As an example: Dones (appendix B-9) showed that greenhouse gas emissions from future fossil power plant systems will be two orders of magnitude higher than future hydro and nuclear and one order of magnitude higher than future PV systems (under Swiss conditions). Such comparisons require careful consideration in order to avoid misleading results. For instance comparison of CO_2-emissions from PV versus coal-fired plants leads to a more advantageous result for PV than comparison with gas-fired plants, because the CO_2-emission of coal plants may be twice as high as that of gas-fired plants.

The most important considerations in technology comparisons are:

- the choice of the reference for the power production technologies with which PV power systems are compared;
- the choice of fuel mix for the electricity production system that supplies to the PV manufacturing plants;
- grid/storage aspects.

Regarding the non-PV reference, simple comparisons on a kilowatt-hour basis between (grid connected) PV and, e.g. coal power plants, can give a meaningful first impression of relative energy and environmental performance. Due to the climate-dependency of PV system

performance, however, such comparisons will always be more-or-less site-specific.
The best choice for the reference technology will depend on the objectives of the study. In a study on future large-scale penetration of PV power production, for example, one should select the 'marginal' power production technology as a reference instead of an average mix of power plants. By 'marginal' technology we mean the type of plants whose electricity production will most likely be substituted by the PV electricity.
In the Netherlands, for example, the reference technology would be gas-fired combined-cycle plants because electricity from PV power systems will replace electricity production from these middle-load power stations.

In (comparative) analyses the fuel mix in the electricity supply system also plays a role in the determination of the environmental profile of the PV power system itself. As was mentioned earlier, a large part of the emissions in the life cycle of PV power systems is caused by the use of energy, electricity in particular. Therefore, the environmental profile of the electricity mix has a strong influence on the environmental profile of PV power systems. A single 'generic electricity mix' (as suggested in Session 4 on LCA) or a regional (e.g. Western-Europe) mix may be used in the analyses in order to make the results more comparable. For international comparisons this may be attractive, but for local decision making such results would have limited practical value. In such cases a local mix might be more consistent with the goal of the analysis.

When large-scale integration of PV power systems into the electricity system is foreseen, simple comparisons between PV and a single non-PV technology is no longer adequate. In such cases backup and storage systems will play a crucial role and comparisons should be between (national or regional) electricity production systems with or without substantial PV power systems including storage provisions.
In such system-wide comparisons one can also consider new concepts for the energy supply system, for example systems with hydrogen as a major energy carrier.

An issue not specifically addressed yet is the question which environmental impacts and indicators for these impacts have to be addressed in the comparative analysis of PV power systems. There is no single, widely accepted indicator that expresses all environmental aspects of PV power systems. Energy payback times and CO_2 mitigation potentials have frequently been used. As long as energy use is strongly based upon the use of fossil energy carriers, there is a strong correlation between these two indicators. In addition, a large part of the emissions from the life-cycles of PV power systems originates from the use of energy. Therefore indicators based upon energy use (like energy pay back times) can be considered as a useful 'driver' in comparative environmental assessments. On the other hand, since energy use is poorly related to risks associated with the use and management of toxic materials it is vital to supplement analyses with HSE information.

Session 7 - Concluding Session

In this session the conclusions and recommendations from the main sessions were summarized by the chair persons and discussed. These results have been incorporated in the sections above and will not repeated here.
In general the participants expressed as their opinion that this workshop had been very useful. At other occasions (like PV conferences) environmental aspects are not given a specific place in the program and the presentations in this field are usually dispersed over different sessions. The value of a dedicated workshop like this is that methods and results can be compared and discussed so that more insight is gained in methodological approaches, areas of consensus and remaining white spots.
It was agreed that we should try to organize a special session on PV environmental aspects during one of the upcoming PV conferences. Among others the results of this workshop could be presented at such an occasion.

Finally the possibilities for further exchange of information through an international expert network were discussed. Novem, the Netherlands Agency for Energy and the Environment, kindly offered that they could provide financial support for such international exchange activities.
One recommendation from the workshop was to set up a dedicated Internet discussion group. This recommendation has been put into effect shortly after the workshop (see textbox).
Also it was felt that a follow-up workshop after about two years would quite be useful. Sørenson indicated that Roskilde university might be prepared to host such an event.

The Internet discussion list on:

"Health, Safety and Environmental Aspects of Photovoltaic Technology"

is an initiative is taken by Utrecht University following the IEA Expert Workshop "Environmental Aspects of PV Power Systems". During this workshop the need was expressed to follow up on discussions that were held during the workshop and in general to establish a closer collaboration between the experts in this field.

Our thought was that a discussion list for professionals might be helpful in achieving this goal. In an Internet discussion list discussions can be held by exchange of E-mail messages. Messages sent to the list will be distributed among all subscribers, who can then just read it or - preferably - give their reaction. Of course the list may also be used to inform others on new reports, conferences papers etc. Also it is possible to distribute or make available files by way of the discussion list.

In order to maintain a certain scientific level and to stimulate frank discussions we have chosen to set up a list which is NOT open to the public. Subscription is open only to: "persons actively involved in research or management of PV Health, Safety and Environmental issues".

This means that all exchanges via the list will only be distributed among a selected group of experts.
Subjects which may be discussed are a.o.:
- Life Cycle Assessment of PV;
- Energy Pay-Back Time and CO2 mitigation potential;
- Health and Safety issues in PV manufacturing;
- Recycling of PV system components;
- Comparative assessment of PV and other energy technologies.

If you are interested and want to subscribe please send a description of your professional position and interests to the listowner:
"Alsema@chem.ruu.nl"

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Appendix A Organization

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A-3 Workshop program

Wednesday 25 june

11.00 - 12.00 Registration & coffee

12.00 - 13.00 Lunch

Session 1: Starting Session (wednesday 25 june, 13.00-17.00)

Chairpersons: Jacques Kimman & Evert Nieuwlaar

13.00 - 13.10 Welcome (Eric Lysen, Novem, The Netherlands)
13.10 - 13.30 Introduction of participants

Presentations:
13.30 - 13.50 Introduction to the workshop (Jacques Kimman, Novem, The Netherlands)
13.50 - 14.10 Utilities perspective (Ola Gröndalen, Sydkraft Konsult AB, Sweden)
14.10 - 14.30 Utilities perspective:Powering towards sustainability: policy of the Dutch Electricity Generating Sector for a sustainable energy supply. (Daniel Dijk, Dutch Electricity Generating Board, The Netherlands)
14.30 - 14.50 Industry perspective (Mike Patterson, BP Solar, UK)
14.50 - 15.00 Questions/discussion on perspectives

15.00 - 15.30 coffee/tea break

15.30 - 16.00 Environmental Aspects of Photovoltaic Power Systems: Issues and Approaches (Evert Nieuwlaar, Utrecht University, The Netherlands)

16.00 - 17.00 **Discussion**
- Major topics/issues
- approaches
- workshop objectives

17.30 - 19.00 Dinner

Session 2: Health, Safety and Environmental (HSE) aspects of cell technologies (Wednesday 25 june, 19.00-21.30)

Chairperson: Vasilis Fthenakis

Presentations:

19.00 - 19.30 Prevention and Control of Accidental Releases of Hazardous Materials in PV Facilities (Vasilis Fthenakis, BNL, USA)

19.30 - 20.00 The management of wastes associated with thin film PV manufacturing (Mike Patterson, BP Solar, UK)

20.00 - 20.30 HSE for CdTe- and CIS-thin film module operation (Hartmut Steinberger, Fraunhofer Institute, Germany)

20.30 - 20.45 coffee break

20.45 - 21.30 **Discussion**

- identification of points for potential concern
  - cadmium compounds;
  - storage/handling of explosive/toxic gases
- module waste considerations
- fire-induced emissions from installed modules

Session 3: Energy Pay-Back Times (EPT) and CO2 mitigation potential (Thursday 26 june, 9.00-12.00)

Chairperson: Bent Sørensen

Presentations

9.00 - 9.30 Understanding Energy Pay-Back Time: methods and results (Erik Alsema, Utrecht University, The Netherlands)

9.30 - 10.00 EPT &CO_2 Payback Time by LCA (Atsushi Inaba, NIRE, Japan)

10.00 - 10.30 Energy Payback Time and Life-Cycle CO_2 Emission of Residential PV Power System with Silicon PV Module (Kazuhiko Kato, MITI, Japan)

10.30 - 10.45 coffee break

10.45 - 11.30 **Discussion:**

- take away misconceptions regarding EPT values for PV
- understanding & interpretation of EPT and CO2 mitigation potential
- guidelines for calculation and use
- EPT and CO2 mitigation potential as performance criteria?

11.30 - 12.30 Visit to PV sound screen system (5 min. walk from hotel)

12.30 - 13.30 Lunch

Session 4: Environmental Life-Cycle Assessment (Thursday 26 june, 14.00-17.00)

Chairperson: Bent Sørensen

Presentations

14.00 - 14.30	Life Cycle Assessment of Photovoltaic Systems: Results of Swiss Studies on Energy Chains (Roberto Dones, Paul Scherrer Institute., Switzerland)
14.30 - 15.00	LCA of a ground-mounted and building integrated PV system (Angelika Bauman, NPAC, UK)
15.00 - 15.30	Reducing ES&H Impacts from Thin Film PV (Kenneth Zweibel, NREL USA)
15.30 - 16.00	Metabolism of sustainable Electricity Supply exemplified with PV (Markus Real, Alpha Real AG, Switzerland)

16.00 - 16.15 coffee/tea break

16.15 - 17.00 **Discussion**

- data availability/quality
- assumptions used/to use
  - future commercial production technology
  - environmental profile of conventional electricity production
- environmental risks associated with emissions
- module encapsulation issues
- interpretation of results
- identification of major life-cycle improvement options
  - recycling
  - resource use

Evening program:

18.00 Departure by bus to Amsterdam, visit the Nieuw-Sloten PV project, dinner offered by Novem

Session 5: System Aspects (Friday 27 june; 9.00 - 12.30)

Chairperson: Muriel Watt

Presentations

9.00 - 10.00	Life Cycle Assessment of Household Energy Systems based on Stand-Alone PV Based Power Supply, Grid Connected PV & Grid Supply (2 presentations, Muriel Watt, Mark Ellis, Aaron Johnson, University of New South Wales, Australia)
10.00 - 10.30	Opportunities and Caveats in moving Life Cycle Analysis to the system level.(Bent Sørensen, Roskilde University, Denmark)

10.30 - 10.45 coffee break

10.45 - 11.15 Life-cycle analysis of building-integrated systems - Optimal solutions for reduction of CO2 emissions (Paolo Frankl, INSEAD, France)
11.15 - 11.45 LCA of PV batteries (Jaap Kortman, IVAM, The Netherlands)

11.45 - 12.30 **Discussion on System aspects**

- Importance of BOS components in environmental profile
- Use of (LCA) results in policy decisions

12.30 - 13.30 Lunch

Session 6: Comparative Assessment (Friday 27 june, 13.30-14.30)

Chairperson: Ken Zweibel

Discussion on Comparative Assessment

- How to compare power sources vs. energy sources
- Comparing different environmental impacts
- Comparison between PV-technologies
- Comparison with other energy technologies

14.30 - 14.45 coffee/tea break

Session 7: Concluding Session (Friday 27 june; 14.45-16.00)

Chairperson: Evert Nieuwlaar

Discussion

- conclusions from previous sessions
- Environmental bottlenecks and opportunities of PV Power Systems
- information needed
- ‘hot spots’
- Approaches to be used
- Guidelines
- R&D issues and reccommendations
- priorities
- options for research & information network
- Involvement of the PV industry

16.00 Closing of the workshop

Appendix B Papers delivered to the workshop

Papers indicated with a star (*) have been modified or revised after the workshop.

B-1 Ola Gröndalen
Aspects and Experiences on PV for Utilities in the Nordic Climate

***B-2** Evert Nieuwlaar
Environmental Aspects of Photovoltaic Power Systems: Issues and Approaches

***B-3** Vasilis M. Fthenakis
Prevention and Control of Accidental Releases of Hazardous Materials in PV facilities

B-4 Mike H. Patterson
The Management of Wastes associated with thin film PV Manufacturing

***B-5** Hartmut Steinberger
HSE for CdTe- and CIS-Thin Film Module Operation

***B-6** Erik Alsema
Understanding Energy Pay-Back Time: Methods and Results

B-7 Atsushi Inaba
EPT and CO_2 Payback Time by LCA

***B-8** K. Kato, A. Murata, and K. Sakuta
Energy Payback Time and Life-Cycle CO_2 Emission of Residential PV Power System with Silicon PV Module

***B-9** Roberto Dones and Rolf Frischknecht
Life Cycle Assessment of Photovoltaic Systems: Results of Swiss Studies on Energy Chains

***B-10** Angelika E. Baumann
Life Cycle Assessment of a Ground-Mounted and Building Integrated Photovoltaic System

B-11 Ken Zweibel
Reducing ES&H Impacts from Thin Film PV

***B-12** A.J. Johnson, M. Watt, M. Ellis and H.R. Outhred
Life Cycle Assessments of PV Power Systems for Household Energy Supply

B-13 A.J. Johnson, H.R. Outhred and M. Watt

An Energy Analysis of Inverters for Grid-Connected Photovoltaic Systems

***B-14** Bent Sørensen
Opportunities and Caveats in Moving Life-Cycle Analysis to the System Level

B-15 P. Frankl, A. Masini, M. Gamberale, D. Toccaceli
Simplified Life Cycle Analysis of PV Systems in Buildings, Present Situation and Future Trends